A Model for GW Emission from CCSN Explosions

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What is the mechanism of explosion?
Multi-Messenger Astrophysics: Exhibit A
Learn from GW?
Indirect

Direct
Neutrino Mechanism:
- Neutrino-heated convection
- Standing Accretion Shock Instability (SASI)
- Explosions? Maybe

Acoustic Mechanism:
- Explosions but caveats.

Magnetic Jets:
- Only for very rapid rotations
- Collapsar?
Mechanism is inherently multi-dimensional
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GW Emission
Explosion Dynamics
Theory: to appreciate what we can learn from GWs
Fundamental Question of Core-Collapse Theory

Steady-State Accretion

Explosion

\[ t = 0.280 \text{ s} \quad \text{?} \quad t = 0.750 \text{ s} \]
**Neutrino Mechanism:**
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**Acoustic Mechanism:**
- Explosions but caveats.

**Magnetic Jets:**
- Only for very rapid rotations
- Collapsar?
Explosions!
(No Solution)

Critical Curve

Steady-state accretion
(Solution)

$L_{ve}$

$\dot{M}$

Burrows & Goshy ‘93
Steady-state solution (ODE)
Is a critical luminosity relevant in hydrodynamic simulations?
How do the critical luminosities differ between 1D and 2D?
Nordhaus et al. ‘10
Why is critical luminosity of 2D simulations ~70% of 1D?
Turbulence
A Theoretical Framework

Solutions for successful explosions

• Develop Turbulence model for CCSN
• Use 3D simulations to calibrate
• Derive critical curve with turbulence
• Use turbulence model in 1D rad-hydro simulations
  o Quick self consistent explosions
  o Systematic investigations of explosions, NS masses, etc.
Murphy, Ott, and Burrows, ‘09
Source Region for GWs?
Characteristic GW frequencies and amplitudes?
$N^2 < 0$
Convectively unstable

$N^2 > 0$
Stably stratified
(gravity waves)
\[ N^2 < 0 \]
Convectively unstable

\[ N^2 > 0 \]
Stably stratified
(gravity waves)

\[ b(r) = \int N^2 dr = \text{buoyant accel.} \]
The Model: Buoyant Impulse

\[ b(r) = \int N^2 dr \]

\[ R_b = \frac{\Delta b D_p}{v_p^2} \]

\[ D_p \sim \frac{v_p}{N} \]

\[ f_p \sim \frac{N}{2\pi} \]

\[ h_+ \propto f_p v_p \]

Similar analysis for 3D convection in stellar interiors
(Meakin & Arnett 2007, Arnett & Meakin 2009)
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Similar analysis for 3D convection in stellar interiors

(Meakin & Arnett 2007, Arnett & Meakin 2009)
$f_p \sim N/(2\pi)$
Progenitor Mass and \( \nu \) Luminosity Dependence
\[ h_+ \propto f_p v_p \]
\[ N^2 = \frac{GM_r}{r^3} \left( \frac{1}{\Gamma_1} \frac{d\ln P}{d\ln r} - \frac{d\ln q}{d\ln r} \right) \]
\[ N^2 = \frac{GM_r}{r^3} \left( \frac{1}{\Gamma_1} \frac{d\ln P}{d\ln r} - \frac{d\ln \rho}{d\ln r} \right) \]

Dense matter EOS

Local Thermodynamics and Neutrino transport
Summary

GW Emission
• Explosion Mechanism
• Protoneutron Star Structure
• Dense Matter EOS
• Explosion Dynamics